

IRAS 0421+0400: jets crossing an ISM/IGM interface ?

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Abstract. The emission lines in the active galaxy IRAS 0421+0400 show a dramatic ($\approx 900 \text{ kms}^{-1}$) increase in the velocity spread at the position of radio hotspots which are located at the beginning of extended radio lobes . We study a model which explains this phenomenon as the result of a jet emerging through the boundary between the interstellar and intergalactic medium . A similar scenario has previously been suggested as an explanation for wide angle tail radio sources (WAT's) . Based on our model, we simulate the longslit spectra of these regions and compare the results with the observations and find that it can explain most of the details in the observed longslit spectra.

1. Introduction

The active galaxy IRAS 0421+0400 was first detected with IRAS (Soifer et al, 1984) and has a redshift of $z=0.046$ (Beichman et al, 1985; Hill et al, 1988). It shows emission line dominated spiral structure and a Seyfert-2-type spectrum . The radio structure is very unusual, consisting of a central 1 arcsec double source in the central region and large symmetrically bent lobes ($\sim 25 \text{ kpc}$). The position of the hotspots as well as the the orientation and bending of the lobes (Beichman et al, 1985; Hill et al, 1988; Holloway et al, 1996; Steffen et al, 1996) appear to be associated with the underlying optical spiral structure of the galaxy.

Jets in FR I radio galaxies can flare very abruptly and show very large opening angles up to 90° in diffuse lobes or tails (O'Donoghue et al. 1993). These structures often bend very near the flaring point as is the case for IRAS 0421+0400. Norman et al (1988) and Loken et al (1995) have modelled this phenomenon in wide angle tail radio galaxies (WAT) in terms of a supersonic jet passing through a shock in the ambient gas where the jet flow becomes subsonic. The jet is then disrupted and entrains external gas, which becomes turbulent and large and small scale eddies then develop. Such a shock in the ambient medium could be due to a supersonic galactic wind moving into the surrounding intergalactic

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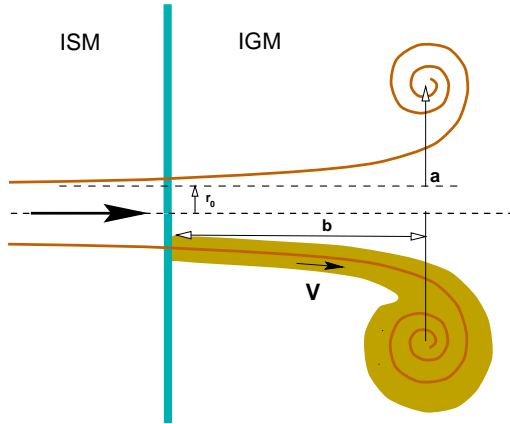


Figure 1. In this line drawing the geometric model parameters of the flow are illustrated. They are the initial radius of the circular cross section r_i , the distance b of the eddy from the transition region where the emission is assume to start, and the distance a from the axis.

medium. We suggest that a similar scenario applies to IRAS 0421+0400 at the position of the radio hot spots. Here a mixing layer develops around the jet in which ambient gas is accelerated. The optically radiating gas should therefore be concentrated in a layer forming an opening quasi-conical surface, possibly with large scale eddies at some point as suggested by hydrodynamical simulations.

Owen et al (1990) conducted a search for optical line emission from the flaring regions in WAT sources but found no significant emission from the 5 objects they studied. If our interpretation is correct, then IRAS 0421+0400 is an important test object allowing to study such a transition region in the optical regime, thereby providing important kinematical information from spatially resolved spectra.

2. The model and optical observations

We model the longslit emission line spectra using a simple parameterized description of the emission and velocity field of the ionized gas flow. In our model we regard the extended emission line source around the radio hot spots as a collimated outflow which flares when passing through the boundary between the ISM and the IGM (see Fig. 2). The radial shape of the flow line is parameterized as a gradually opening spiral (to simulate the effect of possible eddies) given by

$$z_{(s)} = -\frac{a}{s} \cos(s) + \frac{a}{s_0} \cos(s_0) \quad (1)$$

$$r_{(s)} = (r_0 + a(1 - \sin(s)/s))/\epsilon \quad (2)$$

$$\epsilon = (1 - e \cos(\phi))/(1 - e). \quad (3)$$

Here (z, r, ϕ) are cylindrical coordinates, and s is a normalized position parameter along the spiral (the subscript 0 indicates initial values). The parameter a is

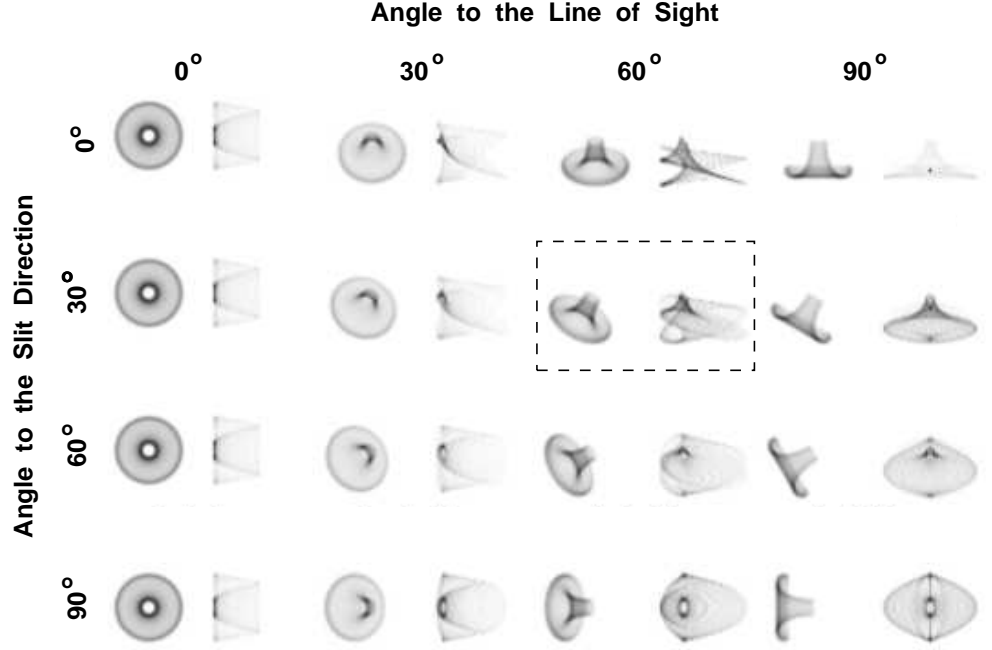


Figure 2. A series of simulations of an opening outflow is shown varying the orientation of the axis with respect to the line of sight (left to right) and with respect to the slit orientation. The slit runs from top to bottom and covers the whole emission. Represented are pairs of images (left) and longslit spectra (right). The simulation marked with a dashed box is shown with more details in the next Figure. In this series it is the best match to the observations at the southern hotspot region in IRAS 0421+0400, and was used as a starting point for more detailed simulations which are compared to the observations below.

the radial distance of the centre of the eddy from the axis, while ϵ allows for an elliptic cross section of excentricity e as a simple approximation to non-axisymmetry.

The longslit line profile is most dependent on the orientation of the outflow with respect to the observer's line of sight and the orientation of the spectrometer slit. The detailed shape of the outflow and the change in emissivity as a function of distance from the starting point only influence the detail of the simulated spectrum and not the gross features. Therefore, we assume a constant emissivity and velocity along the flow line and a gaussian transverse emissivity distribution of $\text{FWHM} = 0.5r_0$.

In Figure 2 we show a series of results for axisymmetric outflows varying the angle with respect to the line of sight (left to right) and orientation with respect to the direction of the spectrometre slit (which covers the whole structure). A logarithmic greyscale is used to emphasize the faint eddies. We find that the structure of the longslit spectrum depends dramatically on the orientation of the outflow. For most orientations the opening section of the outflow produces

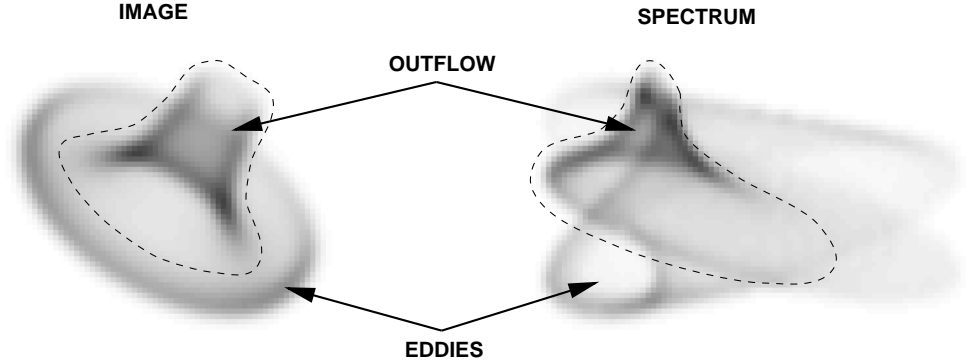


Figure 3. The simulation marked with a dashed line in the previous Figure is shown in more detail. The outflowing material roughly marked with a dashed line in the image simulation (left) basically produces the correspondingly marked region in the longslit spectrum (right). Everything outside this region (and some contribution to the inside region) is originated in the backflow and eddy.

a bright, asymmetric, and also opening feature in the spectrum which is often “V”-shaped. The eddies generally result in a low brightness, diffuse distribution around the brighter emission arising from the outflow.

Table 1. The geometric parameters and the velocity v of the simulations which we compare with the observations are given. The first two rows are axisymmetric simulations of the northern (N) and southern (S) with ellipticity $e = 0$. (Θ, Φ, Ψ) are the Euler angles giving the orientation in space. The other parameters are as shown in a previous Figure.

e		v	Θ	Φ	Ψ	b/a	ro/a
0	(N)	350	65°	0°	30°	0.6	0.02
0	(S)	500	-75°	0°	30°	0.8	0.02
0.8	(S)	500	95°	135°	215°	0.7	0.02

The simulation marked with a dashed rectangle compares quite well with the observed structure in the southern extended emission line region of IRAS 0421+0400. However, the observations show no structures resembling the emission due to the eddies in the simulations (as shown in more detail in Fig. 3). We conclude that the emission line gas in IRAS 0421+0400 is unlikely to be turbulent on large scales.

In Fig. 4 an axisymmetric simulation is shown which reproduce the observed spectra of the hotspot regions in some detail (the values of the geometric parameters and the velocity are given in Table 1). We note, however, that part of the simulated red wing of the southern region is too bright compared to the blue wing. As shown in the same figure, an improvement to this situation is

found by introducing an elliptic cross-section and an emissivity cut-off shortly after the flow turns back.

In Fig. 4 we also compare the predicted emission line image in the hotspot region with the corresponding area in the [O III] 5007-Å image. The latter is a composite of three images of 30 minutes exposure time each, obtained at the Anglo-Australian Telescope (AAT) with an [O III] 5007-Å filter (bandwidth 70Å). The seeing was varying between 1 and 2 arcsec between the individual exposures. It confirms the structure observed previously by Beichman et al (1985), but for the first time shows the predicted “V”-shape of the northern hotspot region and there is some indication for a similar, though less symmetric structure in the south. This supports our interpretation of an opening outflow of emission line gas in the hotspot regions.

3. Conclusions

A simple kinematic model of an opening outflow reproduces the structure found in the longslit emission line spectrum of the hotspot regions in IRAS 0421+0400. The predicted optical image structure of the same regions is confirmed by recent deep [O III] line-imaging. If the proposed model of a jet crossing a shocked boundary between the interstellar and intergalactic medium is correct, then IRAS 0421+0400 provides a unique possibility to study this phenomenon at optical wavelengths.

References

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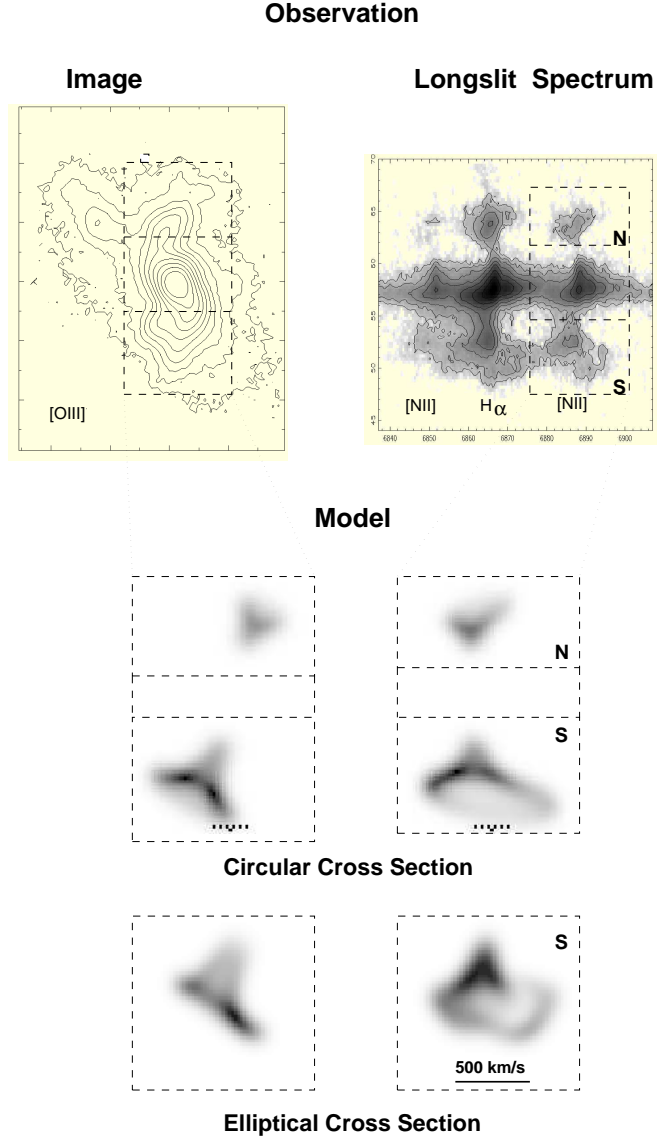


Figure 4. The top panels show the observed preliminary emission line image ([OIII], left) and the longslit spectra (H_{α} -complex, right) at the same scale. Observe the flaring of the spectra at approx. 5 arcsec to the north and south of the centre. The middle panels show the predicted model image of the flaring region (left) in the case of an axisymmetric outflow and the corresponding spectrum (assuming constant velocity along the opening cone of emission line gas). Note the bifurcations ("snake tongues") in the observed [OIII]-image which we identify with the opening outflow. The bottom row shows a similar simulation of the southern hot spot region, but with an elliptic cross section. All simulations were smoothed to a resolution comparable to those of the observations.